91602
new 82-10

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part

ontario hydro
research division

DEVELOPMENT OF AN ON-POWER LEAK SEALANT FOR PNGS "A" BIOLOGICAL SHIELD COOLING SYSTEM

A.S. Williamson, Chemical Research Department
M.T. Flaman, Mechanical Research Department
M.J. Ruysseveldt, Mechanical Research Department

ABSTRACT

The calandria vault concrete of the four PNGS "A" units functions as a biological shield and requires cooling to prevent heat from the reactors degrading the integrity of the concrete. The cooling is done by circulating demineralised water through arrays of 32.5 mm ID, Schedule 80, carbon steel piping embedded in the concrete. The same system also cools the calandria end shield rings, ring thermal shields and ion chamber housings. Sections of exposed piping have developed leaks and an epoxy sealant developed by NNC, UK, has been used to effect in-situ repairs off power. The process is inconvenient, time consuming, and produces substantial volumes of difficult to handle, organic contaminated aqueous waste. An on-power leak sealant intended for the in-situ repair of leaks in the cooling systems has been developed. The product is based on carbon fibres and either an emulsion or silicate adhesive. The sealant is inert, will not affect the cooling system water chemistry, and the carbon fibre particles will not be activated by exposure to neutron flux and should be resistant to gamma radiation. Performance tests in a test loop at Research Division showed the material could effectively seal defects ranging from hairline cracks to 1.0 mm holes at leak rates up to 580 L/h. Durability tests of up to 43 days with periods of depressurisation did not lead to any seal failures. Waste is restricted to the small quantity of excess carbon particles which are removed from the system when the leaks are sealed.

job	file	date	report no.
21-191-551	825.17	August 19, 1991	91-192-K

92-03493/

ontario hydro
research division

EXECUTIVE SUMMARY

DEVELOPMENT OF AN ON-POWER LEAK SEALANT FOR PNGS "A" BIOLOGICAL SHIELD COOLING SYSTEM

A.S. Williamson, Chemical Research Department
M.T. Flaman, Mechanical Research Department
M. Ruysseveldt, Mechanical Research Department

The calandria vault concrete of the four PNGS "A" units which also functions as a biological shield requires cooling to prevent heat from the reactors degrading the integrity of the concrete. The cooling is done by circulating demineralised water through arrays of 32.5 mm ID, Schedule 80, carbon steel piping embedded in the concrete. The same system also cools the calandria end shield rings, ring thermal shields and ion chamber housings.

Sections of exposed piping in the vaults have developed leaks as a result of stress corrosion cracking. Accessibility problems prevent mechanical repair of the affected piping so an epoxy sealant developed by NNC, UK, has been used to effect in-situ repairs off power. The procedure requires the defective section of pipe to be isolated, filled with sealant then drained and flushed out with water. This process is inconvenient, time consuming, and produces substantial volumes of difficult to handle, organic contaminated aqueous waste.

A joint research project to develop an on-power leak sealant was undertaken by the Chemical and Mechanical Research Departments for Retubing Projects. The objective was to formulate a simple, inert, on-power leak sealant that could be added to the bulk coolant and which could then flow through the system to seal any leak sites irrespective of their location. The reactor could remain on power, there would be no need to isolate piping runs, relatively small amounts of sealant would be required, and excess sealant could be removed by filtering. Any reoccurence of leaks could be remedied easily by a repeat application of sealant.

A sealant test loop with three pipe sections was built for assessment of the performance of the different sealant formulations. Two of the three test sections were 32.5 mm ID,

job	file	date	report no.
21-191-551	825.17	August 19, 1991	91-192-K

Schedule 80 carbon steel pipe with each section containing three drilled holes of 0.5 mm, 0.75 mm, and 1.0 mm diameter. The third test section was 38 mm ID Lexan piping with a 13 mm long by 0.25 mm wide circumferential slit through the wall. The equivalent hole size for all three test sections is 2.80 mm diameter. For the final test run an axial crack was produced in a pipe section by cutting a 25 mm long by 0.4 mm wide slit, 75% through wall and fracturing the remaining wall with hydraulic pressure. This replaced one of the sections with drilled hole defects.

Loop operating conditions were: about 15 L circulating volume of demineralised water at approximately pH 9 (LiOH), flow rate 1500 L/h, temperature 30°C, average pressure 320 kPa. The steady state leak rate from all three test sections varied with time from about 300 L/h to 580 L/h as a result of wear at the defects. The rate from the axial crack defect alone was 45 L/h.

Criteria for the selection of constituents for possible leak sealant formulations were: materials should not be corrosive or abrasive to carbon or stainless steels, they should be resistant to gamma and neutron radiation, and any waste produced should be easy to treat for disposal. However, in the initial stage of sealant development a number of different solid materials and combinations were examined in various formulations to gain an understanding of the effects of different shape and size of the solid components on plugging efficiency. Similarly several binders were evaluated for adhesive performance.

To achieve complete sealing of all the different defects, 1.0, 0.75, 0.5 mm drilled holes and the 13 mm by 0.25 mm slit, it was necessary that the sealant contained a combination of different solid particle sizes. If the solids were too large, leaks persisted at the smaller defects and if the solids were too small they were ejected from the system through the large holes. It was found that a mixture of carbon fibres provided effective performance and, as they are inert, they were selected exclusively for sealant optimisation.

Optimisation of the sealant formulation for the various defect geometries in the Research test loop resulted in selection of the following composition:

IM1800 carbon fibre	20g
AS1815 carbon fibre	12g
AS2-12K carbon powder	8g
Binder	60g (either silicate or emulsion)

Only sufficient binder to coat the fibres is necessary, if too much is added it washes off in the flowing water.

Typically, the addition of 10g of this sealant composition to the test loop resulted in leak rates being reduced from several hundreds of litres per hour to minor weeps within 10 to

30 minutes of addition. After 24 hours of circulation the pipe sections would be dry and excess sealant would be removed from the system. Sealant integrity was maintained over test runs of up to 43 days with periods of system depressurisation and even pressure shocks failing to cause reoccurence of leaks.

The sealant is inert and will not affect the cooling system water chemistry. Waste is restricted to the small quantity of excess carbon particles which are removed from the system when the leaks are sealed. These together with the filter bag could be handled as incinerable waste. The carbon fibre particles which construct the seal will not be activated by exposure to neutron flux and should be resistant to gamma radiation.

It is considered that sealant testing has gone as far as possible in the test loop and it is recommended that efforts be made to arrange a field trial in one of the PNGS "A" biological shield cooling systems.

91601
new 82-10

ontario hydro
research division

To Mr. B.J. Murdoch
Manager - Retube Engineering
H18 A15

DEVELOPMENT OF AN ON-POWER LEAK SEALANT FOR PNGS "A" BIOLOGICAL SHIELD COOLING SYSTEM

A.S. Williamson, Chemical Research Department
M.T. Flaman, Mechanical Research Department
M. Ruysseveldt, Mechanical Research Department

The calandria vault concrete of the four PNGS "A" units which also functions as a biological shield requires cooling to prevent heat from the reactors degrading the integrity of the concrete. The cooling is done by circulating demineralised water through arrays of 32.5 mm ID, Schedule 80, carbon steel piping embedded in the concrete. The same system also cools the calandria end shield rings, ring thermal shields and ion chamber housings.

Sections of exposed piping in the vaults have developed leaks as a result of stress corrosion cracking. Accessibility problems prevent mechanical repair of the affected piping so an epoxy sealant developed by NNC, UK, has been used to effect in-situ repairs off power. The procedure requires the defective section of pipe to be isolated, filled with sealant then drained and flushed out with water. This process is inconvenient, time consuming, and produces substantial volumes of difficult to handle, organic contaminated aqueous waste.

Development of a simple on-power leak sealant that could be added to the bulk coolant and which could then flow through the system to seal any leak sites irrespective of their location would have many benefits. The reactor could remain on power, there would be no need to isolate piping runs, relatively small amounts of sealant would be required, and excess sealant could be removed by filtering. Any reoccurence of leaks could be remedied easily by a repeat application of sealant.

Following an evaluation of commercial automobile radiator sealants, (OHRD Report B90-28-K), a joint research project to develop a special on-power leak sealant was undertaken by the Chemical and Mechanical Research Departments for Retubing Projects. This report describes the various compositions and the procedures followed to establish their performance and acceptability.

Test Loop and Procedures:

Figure 1 shows the layout of the sealant test loop. Two of the three test sections were 32.5 mm ID, Schedule 80 carbon steel pipe with each section containing three drilled holes of 0.5 mm, 0.75 mm, and 1.0 mm diameter. The third test section was 38 mm ID Lexan piping with a 13 mm long by 0.25 mm wide circumferential slit through the wall. The equivalent hole size for all three test sections is 2.80 mm diameter. For the final test runs an axial crack was produced in a pipe section by cutting a 25 mm long by 0.4 mm wide slit, 75% through wall and fracturing the remaining wall with hydraulic pressure. This replaced one of the sections containing drilled hole defects.

Loop operating conditions were: about 15 L circulating volume of demineralised water at approximately pH 9 (LiOH), flow rate 1500 L/h, temperature 30°C, average pressure 320 kPa. The steady state leak rate from all three test sections varied with time from about 300 L/h to 580 L/h as a result of wear at the defects. The rate from the axial crack defect alone was 45 L/h.

Short duration test runs were used for the initial screening of sealant compositions. In these the sealant was added to the loop, circulated for 60 minutes at which time excess sealant was filtered out, and the run was continued for 3 hours. The loop was then shut down overnight and restarted the next day to determine whether sealing capability had been maintained.

As the sealant composition was refined the procedure was changed to running the loop for 24 hours with the sealant circulating, the excess material was removed and the loop run for 7 to 43 days.

Details of the different sealant compositions and their performance are given in Appendices 1 and 2.

Discussion:

The following criteria were set for the selection of constituents for possible leak sealant formulations: materials should not be corrosive or abrasive to carbon or stainless steels, they should be resistant to gamma and neutron radiation, and any waste produced should be easy to treat for disposal. However, in the initial stage of sealant development a number of different solid materials and combinations were examined in various formulations to gain an understanding of the effects of different shape and size of the solid components on plugging efficiency. Similarly several binders were evaluated for adhesive performance.

To achieve complete sealing of all the different defects, 1.0, 0.75, 0.5 mm drilled holes and the 13 mm by 0.25 mm slit, it was necessary that the sealant contained a combination of different solid particle sizes. If the solids were too large leaks persisted at the smaller defects and if the solids were too small they were ejected from the system through the large

holes. It was found that a mixture of carbon fibres provided effective performance and, as they are inert, they were selected exclusively for sealant optimisation.

The three grades of carbon fibre chosen for the final sealant formulation were:

IM1800, flake form, 6 mm long, 3 mm wide, filament diameter 8 um.

AS1815, filament form, 6 - 20 mm long, diameter 8 um.

AS2-12K, powder form milled fibre, bulk density 100/250 g/L.

The carbon fibres were supplied by Hercules Inc., Wilmington, DE.

Two adhesive binders were selected for use in the sealant. They were: ethyl silicate, an inorganic resin, and Airflex 465, a proprietary vinyl acetate/ethylene copolymer emulsion adhesive from St. Lawrence Chemicals.

The approach taken in formulation of the sealant was that it should be as easy to use as possible and that one application should suffice to seal any and all leak sites. Therefore, it was decided the material should contain the necessary fibre sizes and quantities to seal all possible defects rather than requiring sequential addition of different fibre sizes. This approach means that if the actual defects in the bioshield cooling system are hairline cracks, the IM1800 fibre will not function as its size will be too large, however, in this case the AS1815 fibre and AS2-12K powder should provide adequate sealing.

Optimisation of the sealant formulation for the various defect geometries in the Research test loop resulted in selection of the following composition:

IM1800 carbon fibre	20g
AS1815 carbon fibre	12g
AS2-12K carbon powder	8g
Binder	60g (either silicate or emulsion)

Only sufficient binder to coat the fibres is necessary, if too much is added it washes off in the flowing water.

Typically, the addition of 10g of this sealant composition to the test loop resulted in leak rates being reduced from several hundreds of litres per hour to minor weeps within 10 to 30 minutes of addition. After 24 hours of circulation the pipe sections would be dry and excess sealant would be removed from the system. Sealant integrity was maintained over test runs of up to 43 days with periods of system depressurisation and even pressure shocks failing to cause reoccurence of leaks.

For the final sealant test, in which one pipe section containing three drilled holes was replaced by the section with the axial crack defect, the crack was sealed within two minutes. The other two sections of the loop in which all leak sites had previously been sealed remained intact during this operation. This test was continued for a total of 36 days without any reoccurence of leakage.

Examination of sealed defects showed that seals are formed by fibres entering the leak site in a vertical orientation then other fibres interlace horizontally with protruding ends of the vertical fibres to form a mat on the internal pipe surface in the region of the defect. Finally the powder component packs into any small interstices in the mat to complete the seal. The binder cures at the air interface to assist in holding the fibres in place.

Coolant conductivity and pH measurements made before addition of the sealant and 24 hours later after removal of excess sealant showed the sealant had no effect on the water chemistry. Initial conductivity and pH values were generally about 43 us/cm and 8.6 respectively. After 24 hours typical values were in the order of 48 - 50 us/cm and 7.8 - 8. These minor deviations probably result from the pure demineralised water used to inject the sealant.

Conclusions and Recommendations:

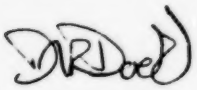
An on-power leak sealant intended for the in-situ repair of leaks in the PNGS "A" biological shield cooling systems has been developed. The product is based on carbon fibres and either an emulsion or silicate adhesive.

Performance tests in a test loop at Research Division showed the material could effectively seal defects ranging from hairline cracks to 1.0 mm holes at leak rates up to 580 L/h. Durability tests of up to 43 days with periods of depressurisation did not lead to any seal failures.

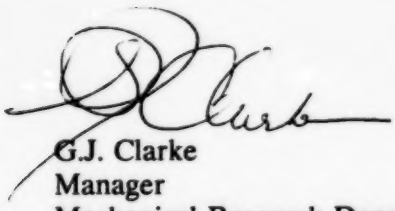
The sealant is inert and will not affect the cooling system water chemistry. Waste is restricted to the small quantity of excess carbon particles which are removed from the system when the leaks are sealed. These together with the filter bag could be handled as incinerable waste. The carbon fibre particles which construct the seal will not be activated by exposure to neutron flux and should be resistant to gamma radiation.

It is considered that sealant testing has gone as far as possible in the test loop and it is recommended that efforts be made to arrange a field trial in one of the PNGS "A" biological shield cooling systems.

Approved by:



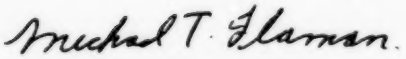
D.J.R. Dodd
Manager
Chemical Research Department



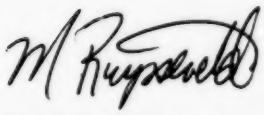
G.J. Clarke
Manager
Mechanical Research Department

Prepared by:

A.S. Williamson
Senior Research Scientist
Chemical Research Department



M.T. Flaman
Unit Head-Structural Integrity
Applied Mechanics Section



M. Ruysseveldt
Technician
Applied Mechanics Section

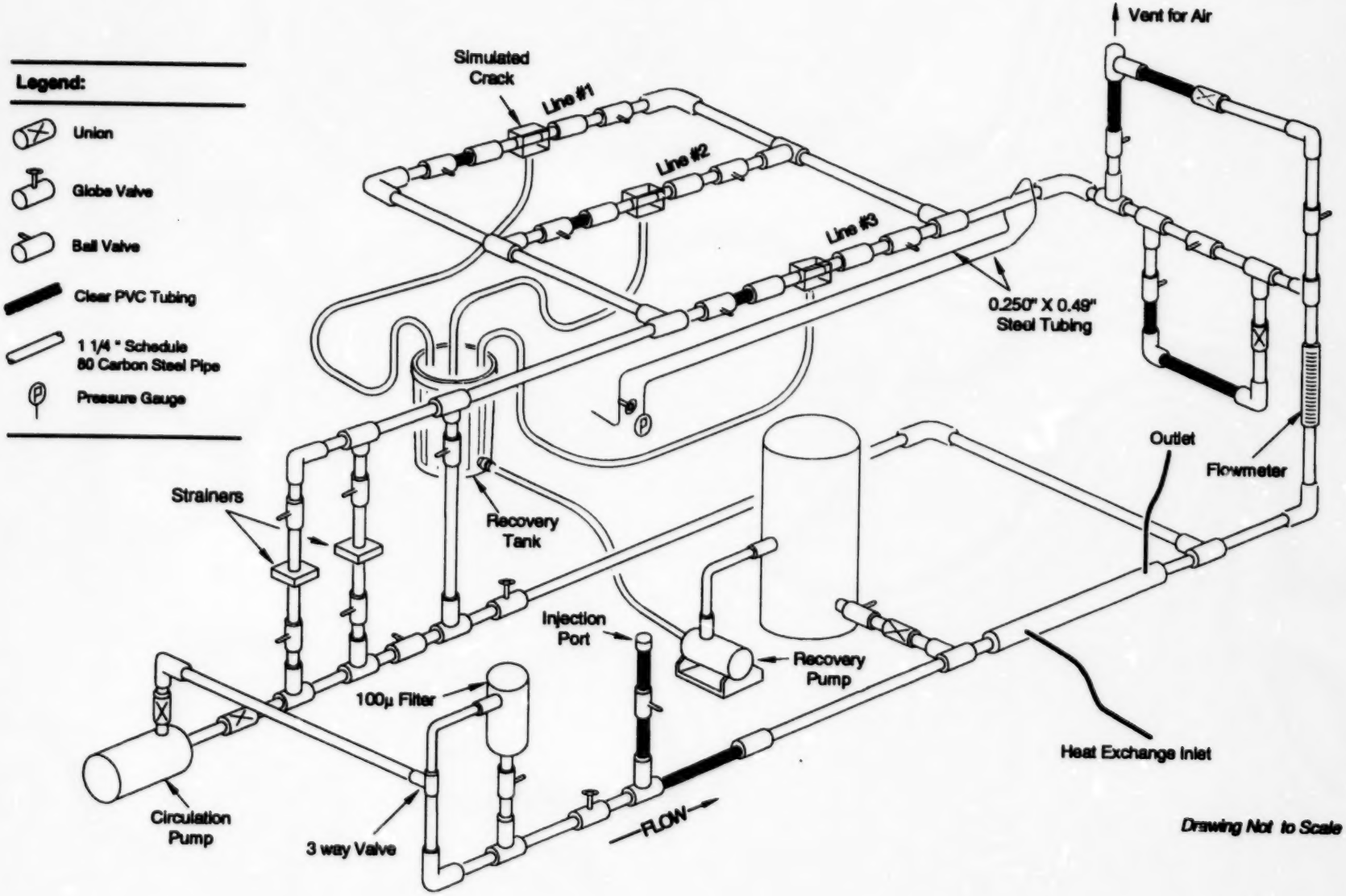


FIGURE 1 BIOLOGICAL SHIELD COOLING SYSTEM SIMULATED TEST LOOP

APPENDIX 1

PRELIMINARY ON-POWER LEAK SEALANT DEVELOPMENT FORMULATIONS

1: 10g.chopped glass fibre
40g bentonite
1OOg sodium silicate

This sealant failed to seal the larger holes in the pipes with all 3 lines operating. Separation of the glass fibres and clay occurred and glass fibres entered the water collection chambers presumably by passing through the larger holes. Valving out pipe runs so that flow was through only one pipe at a time resulted in the holes in lines 3 & 2 becoming sealed. The test was aborted after lh as a result of failure to seal the 1 & 0.75 mm holes in line 1.

Initial leak rate: 245 kg/h

2: 20g chopped glass fibre
40g bentonite
lOOg sodium silicate
6g Acusol 820 (Rohm & Haas

The run was started with line 3 open only and the 3 holes in this line were sealed after 10 mins. Line 2 was then valved in and all 3 holes were sealed after 21 mins. Line 3 was valved in at this time and was sealed at a total time of 33 mins. All seals were intact after lh at which time the filter was valved into the circuit. In the next hour all lines developed minor drips and leaks at various times; in some cases the leaks resealed but total dryness was not achieved.

Initial leak rate: 80 kg/h (line 3 only)
3h leak rate: 17 kg/h

3: 40g chopped carbon fibre
40g fly ash
2OOg Acusol 820

All lines were open for the start of this run. Lines 1 & 3 were completely sealed after 5 mins with only the 0.5 mm hole sealed on line 2. Complete sealing of all lines was achieved after 19 mins. At 40 mins the filter was valved in to remove excess solids. At 49 mins line 3 began to drip at 1 drop/10 secs and after 50 mins the leakage increased from the l mm hole. The leak remained constant up to 52 mins at a rate of 4.8kg/h. Lines 1 & 2 remained completely sealed and dry. (The failure at the l mm hole in line 3 may be due to the use of plastic pipe for the defected area weakening the sealant bond to the surface.

Test stopped after 2h 15mins.

Initial leak rate: 267 kg/h
Final leak rate: 6.5 kg/h

4: 20g chopped carbon fibre
20g bentonite
lOOg Acusol 820

The sealant plugged all leak site within 15 mins. After 40 mins the filter was used to remove solids from the system. Leak tightness was maintained for 3 hours at which time the rig was turned off. The system was restarted the next day after sitting for 18h. All sites remained sealed but for rapid dripping from the 0.75 mm hole in line 1.

Initial leak rate: 247 kg/h
3h leak rate: 0

5: lOg activated carbon
5g carbon black
5g bentonite
40g Airflex 465

All leak sites were plugged within 15 mins of sealant introduction to the loop. At 40 mins the filter and strainers were valved in to the circuit to remove excess solids. There was no reoccurrence of leakage during the 3h test duration.

Initial leak rate: 274 kg/h
3h leak rate: 0

6: 20g carbon fibre
20g activated carbon
5Og Airflex 465

All leak sites were sealed within 18 mins of sealant addition. Strainers and filter valved in after 40 mins. All leak sites remained sealed for 3h with a very slow drip on all 3 lines. The loop was allowed to sit overnight (no pressure) then was restarted. Leakage reoccurred from 1 mm holes on lines 1 & 3.

Initial leak rate: 277 kg/h
3h leak rate: 0
Final leak rate: 35.5 kg/h (after sitting overnight)

7: 25g IRN 78 ion exchange resin
25g Airflex 465

All 0.5 & 0.75 mm holes were sealed within 2 mins but leakage from the 1 mm holes continued unabated. Approximately 20g of a 50/50 mixture of carbon fibres/Airflex 465 was added to the loop after 20 mins, this plugged the main leaks at the 1 mm holes but lines 1 & 3 continued to drip at about 1 drop every 5 secs. Strainers and filter valved in at 40 mins.

Initial leak rate:	270 kg/h
3h leak rate:	2 kg/h

8: 5g chopped carbon fibre
2g activated carbon
5g IRN 78
lOg Airflex 465

Within 3 mins of addition to the loop all holes in lines 2 & 3 were sealed together with both smaller holes in line 1. The 1 mm hole in line 1 became sealed after 12 mins. At 40 mins the strainers and filter were valved in. After 3h there was a slow drip on line 3. The system was shut down for 65h then restarted. Minor leaks were visible on all 3 lines.

Initial leak rate:	27l kg/h
3h leak rate:	0.6 kg/h
Restart leak rate:	36 kg/h

9: 5g chopped carbon fibre
lOg bentonite clay
5g Acusol 820
2g LIOH 10%

The line 3 test section was replaced with a slit defect section for this run, slit size 1.3 mm long by 0.25 mm wide. 4 mins after sealant addition line 3 had sealed to a drip only and the O.5 mm holes on lines 1 & 2 were sealed. At 6 mins all holes in line 2 were sealed, after 13 mins line 1 was completely sealed. At 15 mins line 3 still had a slow drip, the other lines were dry. Leak rate not measurable. The strainers and filter were valved in at 40 mins. After 3h all lines were dry with no leaks and the loop was shut down. After sitting for 18h the loop was restarted. Line 2 was still sealed, line 3 developed a small jet from the centre of the slit, and the 1 mm hole in line 1 was leaking.

Init1al leak rate:	359 kg/h
3h leak rate:	0
Restart leak rate:	62 kg/h

10: 1. 5g chopped carbon fibre
5g bentonite clay
5g IRN 78 IX resin
2g graphite A625
5g Acusol 820
lg 10% LIOH
20g Airflex 465

2. 50g Airflex 465

One minute after sealant injection line 2 was completely sealed, line 3 was still leaking slightly, and line 1 was leaking at the 0.75 mm hole. After 4 mins lines 1 & 3 had slow drips, line 2 was dry. At 10 mins lines 1 & 2 were dry, line 3 still had slow drip. 5Og of Airflex emulsion were added at 14 mins to attempt to adhere more filler to defect areas. At 16 mins all lines were dry and free from drips and remained this way until the loop was.shut down at 3h 13mins. After sitting for approx. 18h the loop was restarted. On line 1 the O.5 mm hole leaked, all three holes on line 2 and the centre of the slit on line 3 leaked.

Initial leak rate:	450 kg/h
3h leak rate:	0
Final leak rate:	98 kg/h

11: 15g Aropol water extendible polymer
3g chopped carbon fibre
3g activated carbon
50g water
2g Acusol 820 emulsion
1g sodium hydroxide

The materials were mixed to form an oil-in-water emulsion which was added to the loop. After 29 minutes, the slit defect and the small and large holes on lines 1 and 2 were sealed but the leaks from the 0.75 mm holes continued unabated. At 39 minutes, leaks from the 0.75 mm holes continued and the slit in line 3 had resumed leaking. The test was concluded at this time.

Initial leak rate: 415 kg/h

12: 10g corn cob material
(sieve analysis: 31% retained on 2.362 mm sieve
17% retained on 2 mm sieve
52% retained on 0.33 mm sieve)

The use of this material was proposed by J.P. Van Berlo, AECL, on the basis of its use at Point Lepreau to plug condenser leaks.

About 5 minutes after injection all leak sites were essentially sealed but there was a slow drip from the slit in line 3. After standing overnight, leaks had resumed from the 0.5 and 0.75 mm holes in lines 1 and 2, and the slit had a fast drip.

Initial leak rate:	443 kg/h
3 hour leak rate:	0
Final leak rate:	22 kg/h

13: 5g AS2-12K milled carbon fibre 275 g/L bulk density
5g AS2-12K milled carbon fibre 100 g/L bulk density

This run was carried out without binder to examine the suitability of the smaller fibre particles produced by milling chopped fibres for leak sealing. It was observed that without the larger sized fibres to provide an initial plug around which the smaller particles could pack, the small particles were ejected through the 1 mm size defects and complete sealing was not possible. Even so, the leak rate was reduced from 461 kg/h to 46 kg/h over a period of 30 minutes.

Initial leak rate:	461 kg/h
3 hour leak rate:	13 kg/h

14: 5g AS2-12K milled carbon fibre 275 g/L bulk density
5g AS2-12K milled carbon fibre 100 g/L bulk density
18g Airflex 465 gel

Within 2 minutes of sealant injection, all defects in lines 1 and 2 were sealed. Slight leaking from the slit defect continued up to 3.5 h at which time the leak rate was 80 g/h. The run was continued for 5 days and only slight dampness was visible at the leak sites.

Initial leak rate:	486 kg/h
Final leak rate:	0

15: 5g IM 1800 carbon fibre
5g milled fibre 275 g/L bulk density
5g milled fibre 100 g/L bulk density
30g Airflex 465 gel

Approximately half the sealant was introduced to the loop. At 30 minutes all lines were essentially sealed the only evidence of leaking being a very slow drip from the slit in line 3. The test was maintained for 5 days.

Initial leak rate:	495 kg/h
Final leak rate:	0.5 kg/h

16: 5g IM 1800 carbon fibre
5g milled fibre 275 g/L bulk density
5g milled fibre 100 g/L bulk density
40g ethyl silicate gel

30g of sealant were introduced to the loop and after 1h all defects were sealed and a zero leak rate achieved. After 24h running, excess sealant in the system was filtered out and the loop was run for 5 days.

Initial leak rate: 547 kg/h
Final leak rate: 0

17: 5g IM 1800 carbon fibre
3g AS 1815 carbon fibre
3g AS2-12K milled fibre 100 g/L
30g Airflex 465 gel

Some 20g of sealant was added to the loop and within 30 minutes all leaks were sealed. After 24h, the excess sealant was removed from the loop which continued running for 5 days. The loop was shut down (depressurised) for 2 days then restarted. On restart after the 2 day shutdown, leakage from the 3 holes in line 2 was evident at a rate of 37 kg/h. About 6g of sealant was added and the leaks resealed within 9 minutes. The loop was run for a further 5 days without any recurrence of leakage.

Initial leak rate: 561 kg/h
Final leak rate: 0

18: 5g IM 1800 carbon fibre
3g AS 1815 carbon fibre
3g AS2-12K milled fibre 100 g/L
15g ethyl silicate gel

Half the sealant was added to the test loop. All leaks were sealed after 15 minutes. After 24h the excess sealant was filtered out and the loop run for a further 4 days without any leakage. The loop was shutdown for 2 days then restarted. Leakage occurred from the 1 mm and 0.75 mm holes in line 1 and the 0.5 mm hole in line 2. The rate was 108 kg/h. The remainder of the sealant was added to reseal the leak sites and the loop was run for another 4 days without any further leaks.

Initial leak rate: 500 kg/h
Final leak rate: 0

19: 5g IM 1800 carbon fibre
3g AS 1815 carbon fibre
2g AS2-12K milled fibre 100 g/L
20g Airflex 465

15g of sealant was added to the loop and all leak sites were sealed in 5 minutes. Excess sealant was removed from the loop after 24h running and the test continued until 5 days had been completed. Circulation in the loop was stopped for 2 days then the system was restarted. No leaks had developed. The loop was operated for another 4 days .

Initial leak rate: 540 kg/h
Final leak rate: 0

20: This was a repeat using the same composition sealant as run 19.

Again 15g of sealant was added and all leaks were sealed within 15 minutes. After 24h excess sealant was filtered out and the loop run for another 4 days before shutting down for 2 days. The loop was restarted and no leaks were present. The run was continued for 16 days and was then shutdown for 6 days. On restart, a leak had redeveloped at the 0.75 mm hole in line 1 which had a leak rate of 1.5 kg/h. 1g of sealant was added and the leak resealed. The loop was run for a further 12 days without problems, giving a total test time of 43 days .

Initial leak rate: 565 kg/h
Final leak rate: 0

21: During this run, line 1 with three drilled holes was replaced with a section of pipe containing an axially oriented crack. The crack was created by cutting a 25 mm by 0.4 mm slit through 75% of the pipe wall thickness then fracturing the remaining wall with hydraulic pressure. The leak rate through this defect alone was 45 kg/h.

The test was done with the same sealant used in runs 19 and 20.

All leaks were sealed within a few minutes and the test was continued for a total of 36 days with no signs of further leakage.

Initial leak rate: 583 kg/h
Final leak rate: 0